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Miyo Yokota, Gaston P. Bathalon, Larry G. Berglund

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Biophysics and Biomedical Modeling Division
U.S. Army Research Institute of Environmental Medicine
Building 42 - Kansas Street
Natick, MA 01760

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14. ABSTRACT
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15. SUBJECT TERMS
anthropometry, thermal regulatory model, heat stress, core temperature, heart rate

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ORIGINAL ARTICLE

Assessment of male anthropometric trends and the effects on simulated heat stress responses

Miyo Yokota · Gaston P. Bathalon · Larry G. Berglund

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Abstract Assessing temporal changes in anthropometrics and body composition of US Army soldiers is important because these changes may affect fitness, performance, and safety. This study investigated differences in body dimensions (height, weight, percent body fat (%BF)) of US Army male soldiers by comparing 2004 and 1988 databases. Anthropometric somatotypes were identified and physiological responses of the different somatotypes to simulated heat stress (35°C/50%rh, ~550 W work rate, carrying 12 kg load including battle dress uniform and body armor, rest for 30 min and walk for 70 min) using a thermal regulatory model were evaluated. A significant increase in body weight (2.4 kg) was observed between the 2004 and 1988 data ($P < 0.05$, after Bonferroni correction). However, changes in height and circumference measurements for %BF were insignificant, with the magnitude of the changes not exceeding inter-observer errors. Multivariate analyses demonstrated that anthropometric distributions did not differ between the two databases and identified five primary somatotypes: "tall-fat", "tall-lean", "average", "short-lean", and "short-fat." Within each database, anthropometric values differed among the somatotypes. However, simulated physiological responses to heat stress in each somatotype were similar in the 2004 and 1988 populations. In conclusion, an increase in body weight was the primary change observed in this sample of US Army male soldiers. Temporal changes in somatotypes of soldiers over a 16-year period had minimal impact on simulated physiological response to heat stress using a thermal regulatory model.

Keywords Anthropometry · Thermal regulatory model · Heat stress · Core temperature · Heart rate

Disclaimer: The investigators have adhered to the policies for protection of human subjects as prescribed in Army Regulation 70-25, and the research was conducted in adherence with the provisions of 32 CFR Part 219. The opinions or assertions contained herein are the private views of the author(s) and are not to be construed as official or reflecting the views of the Army or the Department of Defense.

M. Yokota (✉) · L. G. Berglund
Biophysics and Biomedical Modeling Division,
US Army Research Institute of Environmental Medicine
(USARIEM), Kansas Street, Bldg 42, Natick,
MA 01760-5007, USA
e-mail: Miyo.Yokota@us.army.mil

G. P. Bathalon
Office of the Commander, US Army Research Institute
of Environmental Medicine (USARIEM), Kansas Street,
Bldg 42, Natick, MA 01760-5007, USA

Introduction

Assessing temporal changes in body composition and fitness in US Army personnel is important as these changes may affect soldier performance and safety in the work place (Knapik et al. 2006). Over the past 20 years, excessive weight and obesity among adults has become epidemic in the United States (Centers for Disease Control and Prevention 2006). Similarly, increases in weight and body mass index (BMI) among US Army soldiers have been reported (Friedl 2004; Bray et al. 2006; Knapik et al. 2006). However, changes in muscle endurance of US Army recruits were reported as insignificant while cardiorespiratory endurance declined over the similar time period (Knapik et al. 2006). Although temporal trends in fitness levels are primarily evaluated by quantitative measurements taken from Army Physical Fitness Scores or laboratory tests (Sharp et al. 2002; Westerstahl et al. 2003), guidelines for assessing the level of heat strain to prevent thermal injury and performance impairment are primarily based on physiological (e.g., core temperature, heart rate) and/or environmental parameters (e.g., air temperature) (Centers for Disease Control and Prevention 2002; ISO 2004). Thus, it is important to examine physiological effects of these temporal trends and changes on responses to thermal stresses.

The purpose of this study was to examine the temporal differences in body composition of US Army male soldiers using anthropometric data taken at different time periods and to assess the effects of the temporal changes on simulated individual thermal physiological responses to heat stress. The thermal regulatory simulation model used in this study partitions the human into six compartments (i.e., core, muscle, fat, vascular skin, avascular skin, and central blood) using the first principles of physiology, heat transfer, and thermodynamics (Kraning and Gonzalez 1997). The results of this investigation may be useful in identifying individuals who might be susceptible to heat stress.

Methods

Height, weight, and %BF from two databases, i.e., 2004 ($n = 480$) (Bathalon et al. 2004) and 1988 ($n = 1{,}773$) (Gordon et al. 1989), containing self-reported race/ethnicity of male Army volunteers were compared. The data were collected from Active Duty Army soldiers. The studies were approved by US Army Research Institute of Environmental Medicine Human Use Review Committee and were performed in accordance with AR 70-25, Use of Human Subjects in Research. Body fat was estimated from neck and abdominal circumference measurements taken by trained anthropometrists, consistent with Army Regulation (AR) 600-9 (Department of Army 1987) and using the Department of Defense (DoD) %BF equation (Hodgdon and Friedl 1999). This field expedient body fat equation has been cross validated with other methods (e.g., underwater weighting and dual-energy X-ray absorptiometry), and has been used by the military for over a decade (Friedl et al 1992). The racial/ethnic composition of the Army changed between 1988 and 2004 (more Hispanics/Asians and fewer Whites and Blacks), which might affect the anthropometric distributions in the two populations. Thus, in order to match Army demographic distributions each database was weighted by the race/age distributions provided by the Defense Manpower Data Center (Department of Army 2004).

Anthropometric distributions of the two datasets were compared using univariate statistics and principal component analysis (PCA) (STATA 2003). For univariate statistics, Bonferroni corrections were applied to adjust the significant level of $P = 0.05$ for multiple comparisons. PCA selects linear combinations of multiple variables to maximize variation of the population with a new axis or eigenvector, thereby, summarizing the overall patterns of the multivariate distributions into simpler dimensions. The eigenvalue of each axis explains the amount of variability of the data (Tatsuoka 1988). Because of the large sample size, individual anthropometric variations obtained by PCA were identified by generating an ellipse encompassing 90% of the majority of the populations. Five primary points on the ellipse were selected to represent average and extreme individuals in each population. The anthropometric variables on the ellipse were subsequently incorporated in a thermal regulatory model to examine simulated individual physiological differences to heat stress. All statistical analyses were conducted using STATA 8.0 (STATA 2003).

The thermal regulatory model used in this study, developed by Kraning and Gonzalez (1997), comprising six compartments (i.e., core, muscle, fat, vascular skin, avascular skin, and central blood) is based on human physiology and biophysics of heat transfer and thermodynamics. The model predicts time series of heart rates, core and skin temperatures, and sweating rates of individuals as a function of heat production, anthropometry (height, weight, and %BF), thermal aspects of the physical environment (air temperature, dew point, solar radiation, and wind speed) and clothing characteristics (e.g., insulation and vapor permeability), and physiological state (acclimatization and hydration). The model was validated under various heat stress conditions and the detailed mechanism and functions of the model are described elsewhere (Kraning and Gonzalez 1997).

Using identified anthropometric variables, the model simulated non-acclimatized individuals, wearing battle dress uniform (BDU) and body armor and carrying a total load of 12 kg, rested for 30 min and then walked at 3 mph for 70 min in 35°C/50% relative humidity (rh) (~550 W). The anthropometric effects on core temperature and heart rate responses were examined.

Results

Anthropometry

The anthropometric characteristics of the male soldiers in the 1988 and 2004 databases are summarized in Table 1. The acceptance range of measurement errors according to inter-observer error standards (Gordon and Bradtmiller 1992) is also included. On average, there was a statistically significant increase in weight (2.3 kg). Small increases in BMI (0.6 kg/m^2) and neck circumference (0.4 cm), and a slight decrease in %BF (0.8%) were also observed ($P < 0.05$, after Bonferroni correction). However, the small differences between the two populations were within the tolerance range of measurement error (Gordon and Bradtmiller 1992).

Table 1 Descriptive summary of anthropometric data and tolerance values of inter-observer errors of male soldiers from 1988 and 2004 populations

Anthropometric variable	Database		Inter-observer error range
	1988	2004	
n	1773	480	
Age (years)	29 (7)	28 (8)	N/A
Height (cm)	175.9 (6.6)	176.5 (7.3)	1.1
Weight (kg)	79.3 (11.2)	81.6 (12.2)*	0.3
Body Mass Index (kg/m^2)	25.6 (3.0)	26.2 (3.6)*	N/A
Body fat (%)	18.5 (5.5)	17.7 (6)*	N/A
Body surface area (m^2)	1.95 (0.15)	1.98 (0.16)*	N/A
Neck circumference (cm)	38.1 (2.0)	38.5 (2.3)*	0.6
Abdomen circumference (cm)	87.6 (8.7)	87.2 (9.2)	1.2

N/A not available

Anthropometric values: mean (standard deviation)

* Statistical difference between the 1988 and 2004 databases at $P < 0.05$ (Bonferroni correction with seven measurements)

Table 2 is a summary of PCA results with eigenvalues and eigenvectors that characterize the anthropometric distributions. The first component (X axis) represents 61% (=100 × (1.83/(1.83 + 1.02 + 0.15)) of the total variation and corresponds to all positive loadings of variables in eigenvectors indicating overall size. The second eigenvalue (Y axis) represents 34% (=100 × 1.02/(1.83 + 1.02 + 0.15)) of the total variation and corresponds with the dichotomous somatic shape in eigenvectors, such as "tall-lean" versus "short-fat". The third component, corresponding to a somatotype such as short football players (e.g., short with low fat yet heavy weight), was eliminated from further analyses because it represented only 5% of the total variation.

Figure 1 presents two 90% ellipses representing the 1988 and 2004 populations in the first two principal components shown in Table 2. The results of PCA demonstrated a similar anthropometric distribution between the 1988 and 2004 populations. The somatotypes of extreme individuals in both the populations are defined as "tall-fat (TF)", "tall-lean (TL)", "average (A)", "short-lean (SL)", and short-fat (SF)".

Table 3 lists the anthropometric characteristics, converted from PCA scores, corresponding to the somatotypes shown in Fig. 1. For instance, height, weight and %BF of the tall-lean somatotype from the 2004 population ("TL^{04}", Fig. 1) are 191 cm, 83 kg, and 9%, respectively (Table 3). The anthropometric values were subsequently applied to the thermal regulatory model for physiological comparisons.

Table 2 Principal component analysis summary

Component	Eigenvalue	Difference	Proportion	Cumulative
1	1.83	0.81	0.61	0.61
2	1.02	0.87	0.34	0.95
3	0.15		0.05	1.00
	Eigenvectors			
Variable	1	2	3	
Height	0.42	0.80	0.43	
Weight	0.71	0.00	−0.70	
%Bodyfat	0.56	−0.60	0.56	

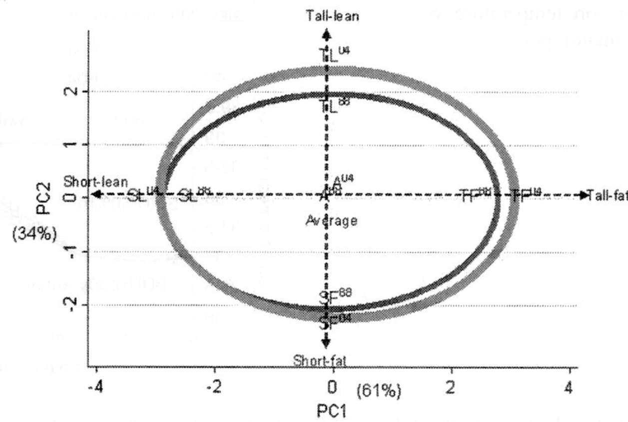


Fig. 1 A two-dimensional plot for the 1988 (*dark gray*, inside ellipse) and 2004 (*light gray*, outside ellipse) male populations. Two ellipses represent 90% of the two populations, corresponding to Table 3 for a description of the five somatotypes

Core temperature (T_{cr})

Figure 2a shows the overall T_{cr} comparisons between the somatotypes in the 2004 population. Within each population, predicted physiological responses were different by somatotypes. Based on the threshold of T_{cr}, as 38.5°C, representing approximately 25% heat casualties (Sawka et al. 2000), "short-lean" individuals were predicted to perform their tasks for up to 89 min in the simulated hot environment (SL^{04} in Fig. 2a), while "tall-fat" somatotype would be expected to perform for only 71 min (TF^{04} in Fig. 2a). "Short-lean" individuals, and to a lesser extent "tall-lean" individuals were predicted to be more tolerant of heat stress

Table 3 Anthropometric values of 1988 and 2004 populations on the 90% ellipse

Primary point	Height (cm)	Weight (kg)	Body fat (%)	A_D (m^2)	Somatotype	Database
A^{88}	176	79	19	1.95	"Average"	1988
A^{04}	177	82	18	1.99	"Average"	2004
TF^{88}	186	106	29	2.30	"Tall-fat"	1988
TF^{04}	186	112	29	2.36	"Tall-fat"	2004
TL^{88}	188	79	10	2.05	"Tall-lean"	1988
TL^{04}	191	83	9	2.12	"Tall-lean"	2004
SL^{88}	166	52	8	1.57	"Short-lean"	1988
SL^{04}	168	55	7	1.62	"Short-lean"	2004
SF^{88}	163	80	27	1.86	"Short-fat"	1988
SF^{04}	161	82	26	1.86	"Short-fat"	2004

A_D = Body surface area

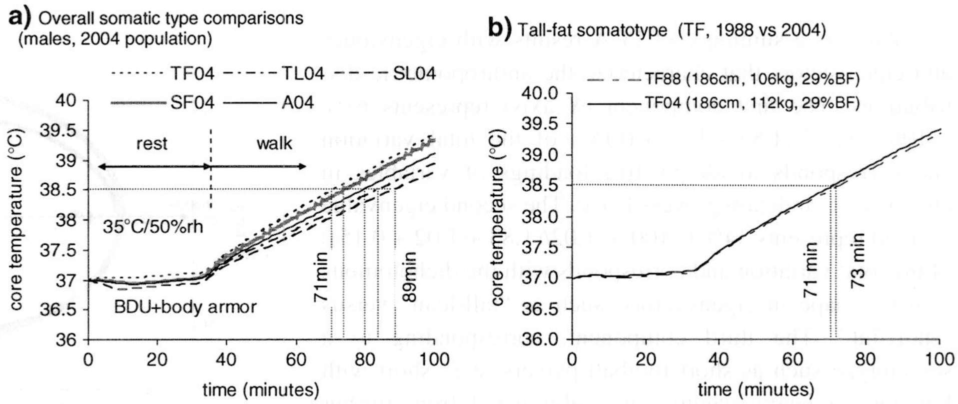


Fig. 2 Anthropometric effects on core temperatures by somatotypes

and able to maintain lower T_{cr} at given time points (SL^{04}, TL^{04} in Fig. 2a). In general, "fat" individuals, whether short or tall, were predicted to experience greater heat strain. As a result, the "lean" individuals were predicted to work 20% longer than "fat" individuals (Fig. 2a). Figure 2b displays the predicted T_{cr} comparisons in "tall-fat" somatotypes of the 1988 and 2004 populations, as an example. Overall, within each somatotype, differences in physiological responses were insignificant between the 1988 and 2004 datasets.

Heart rate (HR)

Figure 3a shows the overall HR response between the somatotypes in the 2004 population. HR in the thermal model is determined as the ratio of required cardiac output (CO_{req}) to stroke volume (SV), where CO_{req} is the summation of blood flow to each compartment. In the model, HR is limited to be not greater than a maximum HR defined as $HR_{max} = 220 - \text{age}$, and CO is limited to a maximum CO of $CO_{max} = HR_{max} \times SV$ (Kraning and Gonzalez 1997). Similar to the T_{cr} results, the simulated HR results showed the biggest differences to be between the "tall-fat (TF^{04})" and "short-lean (SL^{04})" somatotypes, with "short-lean" individuals having lower HR (Fig. 3a).

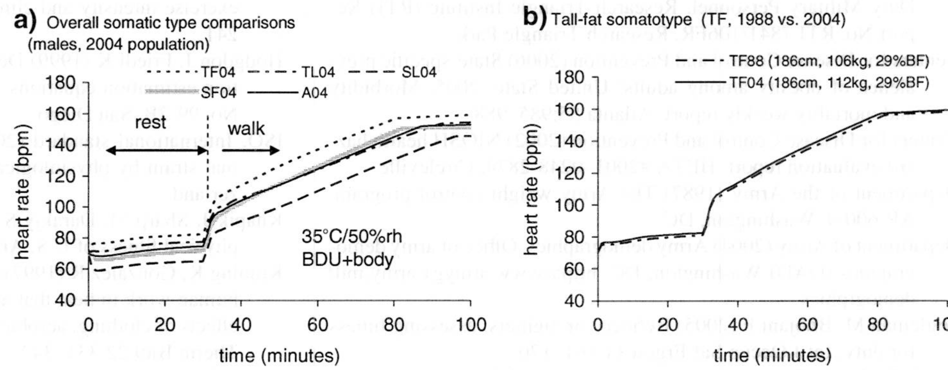
Figure 3b shows the predicted HR responses for the "tall-fat" somatotype of the two populations as an example. Overall, the differences in predicted HR for each somatotype were insignificant between the 1988 and 2004 populations.

Discussion

Temporal trends in anthropometrics, body compositions, and fitness levels in the military are commonly examined to assess health and safety (Greiner and Gordon 1992; Knapik et al. 2006). To our knowledge, assessing the impact of changes in anthropometrics and body composition on simulated physiological responses to exercise and heat stress is rarely reported because such trends are difficult to measure. The present study examined changes in anthropometry and simulated those changes to investigate whether these changes affected a simulated physiological response to heat stress over time, using a thermal regulatory model.

As observed in non-military populations (Centers for Disease Control and Prevention 2006), we observed a significant increase in body weight, even though most complied with weight control standards (Bathalon et al. 2004). Weight increase has been consistently reported in previous military studies (Friedl 2004; Bray et al. 2006; Knapik et al.

Fig. 3 Anthropometric effects on heart rates by somatotypes



2006). However, changes in height and body circumference measurements used to estimate %BF were not significant because the magnitude of the changes did not exceed inter-observer errors. That is, small differences in these measurements may be associated with measurement error made by the different anthropometrists. These results suggest that the relationships between BMI and body composition differ between military and non-military populations. In non-military populations, an increase in BMI associated with increased body weight is generally thought to reflect an increased level of body fatness (Centers for Disease Control 2006). However, a weight increase observed over a 16-year period in soldiers did not necessarily indicate a concomitant increase in body fat. This may be related to stringent age-based weight-for-height guidelines and %BF standards applied by the US Army (Department of Army 1987). Previous studies in military personnel have suggested that an increase in body weight is primarily associated with increases in fat-free mass, rather than fat mass (Friedl 2004; Knapik et al. 2006).

Despite an increase in weight over the 16-year period, the change in each somatotype between the 1988 and 2004 populations had minimal effect on simulated physiological responses to heat stress. Predicted heat tolerance levels differed by five identified somatotypes in multivariate anthropometric distributions. In this study, "short-lean" individuals, having low %BF and a higher body surface per mass, were predicted to maintain a lower T_{cr} and HR for given exercise and environmental conditions. This suggests that the "short-lean" soldier can dissipate core heat more easily because of lower passive thermal resistance between core and skin from less fat, and the larger skin area per unit mass further facilitates the loss of this heat to the environment. In general, the larger skin area per unit mass of short lean facilitates heat loss to the environment more efficiently than fat individuals, when metabolic heat production varies by individual body mass (Ruff 2000; Shapiro 1980). The present model estimates metabolic heat production based on body mass, walking speed, and topography of the subject's activity (Pandolf et al. 1977). Thus, with the simulation model initialized for equal fitness and acclimation levels, the differences in thermal responses in this study were primarily based on fat insulation, body surface area, and metabolic cost adjusted for body mass, identified in the somatotypes.

This study demonstrated that physiological responses to simulated heat stress were different by body size and shape. Previous studies indicate that operational factors (e.g., environmental conditions, physical activity, load carriage, clothing) may affect thermal strain experienced by individuals with different body size and shape in different ways (Fogleman and Bhojani 2005; Frisancho 1993; Havenith et al. 1998). For instance, firefighters whose tasks generally consist of short rescue (~5–10 min) and fast recovery of victims, may benefit from larger body frames with stronger upper body strength (Fogleman and Bhojani 2005). Therefore, when assessing workers' health and safety, it is important to consider thermal strain levels from both operational and somatotype aspects.

Finally, in addition to temporal trends, changes in demographic composition such as age, race, or gender, may result in anthropometric differences within populations. Careful examination of the effects of demographic changes on anthropometry is recommended for accurate assessment of temporal trends in body composition and the effect on thermal regulatory responses.

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